

The role of MSSM heavy Higgs production in the self coupling measurement of the 125 GeV Higgs boson at the LHC

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Abstract

Measurement of the self coupling of 125 GeV Higgs boson is one of the most crucial tasks for high luminosity run of the LHC and it can only be measured in the di-Higgs final state. In the minimal supersymmetric standard model, heavy CP even Higgs (H) can decay into lighter 125 GeV Higgs boson (h) and therefore influence the di-Higgs production. We investigate the role of single H production in the measurement of self coupling of h . We find that $H \rightarrow hh$ decay can nontrivially affect the h self coupling measurement in low $\tan\beta$ regime when the mass of the heavy Higgs boson lies between 250 - 600 GeV and depending on the parameter space it may be seen as an enhancement of the self coupling of 125 GeV Higgs boson.

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1 Introduction

One of the long standing problems of particle physics is the origin of mass of fundamental particles. In the standard model (SM), a scalar doublet is introduced, neutral component (called Higgs boson) of which spontaneously breaks the electroweak symmetry by acquiring the non-zero vacuum expectation value (vev) and consequently generates masses for all SM particles. The mass of the Higgs boson is a free parameter in the SM and it is determined by the vev of the Higgs field and Higgs quartic self coupling (λ). A new boson with a mass about 125-126 GeV has been recently observed by ATLAS [1] and CMS [2] collaborations of Large Hadron Collider (LHC) experiment which may be the only missing piece of the SM, i.e., the Higgs boson. The next crucial step is to measure the properties of the newly discovered boson and establish the connection between this particle and the electroweak symmetry breaking mechanism. The measured couplings of the new boson with fermions and gauge bosons are found to be quite compatible with those of the SM Higgs boson [3, 4] and more accurate measurement will be performed in the near future at the 13/14 TeV LHC [5]. In order to reconstruct the full profile of the Higgs boson, we also need to measure the Higgs self coupling along with other couplings. In the framework of SM, it is possible to determine Higgs self-coupling λ from the accurate measurement of Higgs mass and vev of the Higgs field. However, we should note that this type of estimation is indirect in nature and independent confirmation is indeed required to prove the existence of SM Higgs boson. The direct way to determine the coupling λ is to produce three Higgs bosons through Higgs boson quartic coupling λ in collider experiments. However, triple Higgs boson production cross section is too small to observe at the LHC even with very high luminosity and therefore the only probe is to observe di-Higgs production via Higgs trilinear coupling. Higgs trilinear coupling is generated by the electroweak symmetry breaking and it is proportional to λ and the vev of the Higgs field. It is thus possible to measure the Higgs quartic self coupling λ from the di-Higgs production cross section in the SM [6–8]. The Higgs pair production cross section in the SM is also small (a few tens of fb at the 14 TeV LHC) and it is accessible at the very high luminosity LHC, called HL-LHC.

In 2015, the LHC will start to operate at 13/14 TeV center of mass energy and after 2018 it is expected that the LHC will be upgraded for high luminosity operation. At HL-LHC, prospect of

SM Higgs self-coupling measurement has been studied extensively in Ref [9–15] using Higgs pair production process. Although, we can have various final states like $b\bar{b}b\bar{b}$, $b\bar{b}W^+W^-$, $b\bar{b}\gamma\gamma$, $b\bar{b}\tau\bar{\tau}$, $W^+W^-W^+W^-$ etc. from Higgs pair production, phenomenological studies show that $b\bar{b}\gamma\gamma$ channel is the most promising one [10, 12]. A recent study [5] by ATLAS Collaboration has also confirmed the importance of $b\bar{b}\gamma\gamma$ channel for the measurement of SM Higgs self-coupling.

Precise measurement of Higgs self-coupling and the reconstruction of Higgs potential is necessary in order to prove the correctness of the SM as there are many well motivated scenarios beyond the standard model (BSM) which can have extended Higgs sector and/or non-standard couplings [16–20]. The presence of new particles and couplings can potentially change the value of Higgs self coupling λ compared to that of SM [16–20]. In case, we observe deviation of λ from its SM value, this can be the indication of new physics beyond the SM.

In minimal version of supersymmetric standard model (MSSM), which is one of the most favourable BSM models, there are five Higgs bosons: one CP even light Higgs (h), one CP even heavy Higgs (H), one CP odd Higgs (A) and two charged Higgs bosons (H^\pm). In this scenario, the lightest CP even Higgs boson (h) can be identified with the observed 125 GeV Higgs boson and other Higgs bosons may be discovered in future LHC run. In the MSSM scenario, tree level couplings of Higgs bosons depend on two parameters: Higgs mixing angle α and β , where $\tan \beta$ is the ratio of the vacuum expectation values of two Higgs doublets. This means that Higgs couplings can be significantly different from the SM depending on the parameter space of the model.

In MSSM, one of the important consequences of the presence of heavy Higgs boson is that H can decay to lighter Higgs boson h and in that case, single production of heavy Higgs can be seen as a pair production of lighter Higgs bosons. We already mentioned that the observation of pair production of Higgs boson is the only direct way to measure the self coupling of h and therefore, the production of heavy Higgs boson and its decay to h can potentially affect the measurement of λ . In this paper, we study the effect of heavy Higgs (H) production on self coupling measurement of SM-like Higgs boson h in the context of MSSM. We assume that the observed Higgs with mass 125 GeV is indeed MSSM lightest Higgs boson and the couplings of h is such that it behaves like SM

Higgs boson. The plan of the paper is as follows: in Sec.2 we briefly discuss the production of heavy CP even MSSM Higgs and its decay to lighter Higgs boson. In Sec.3, we introduce the benchmark points for further analysis and study the properties of 125 GeV Higgs in the light of LHC data. In Sec.4 we illustrate how the production of H can influence the self coupling measurement of lighter (SM like) Higgs boson. Summary of our work and possible issues are discussed in Sec.5.

2 MSSM H production and its decay to 125 GeV Higgs

The couplings of the MSSM Higgs bosons are determined by two parameters: α and β defined in the introduction. The couplings of gauge bosons with h and H are proportional to $\sin(\beta - \alpha)$ and $\cos(\beta - \alpha)$ respectively. As the experimental data show that the observed Higgs boson, which is assumed to be h , couples to W/Z gauge boson similar to SM Higgs, $\sin(\beta - \alpha)$ should be close to unity in order to satisfy the above mentioned constraint. In the limit $\sin(\beta - \alpha) \rightarrow 1$, h couples to fermions and gauge bosons exactly like SM Higgs boson. This is quite similar to the case of decoupling limit in which the lightest MSSM Higgs boson behaves like SM Higgs boson. In this case, heavier CP even Higgs H does not couple to electroweak gauge bosons and coupling to up and down type fermions are either suppressed or enhanced by $\tan \beta$. For large values of $\tan \beta$, the coupling of H (also H^\pm and A) to b quark becomes strong as it scales with $m_b \tan \beta$ while its coupling with the top quark, which is $\propto m_t / \tan \beta$, becomes rather weak. In that case, H dominantly decays to b quarks and τ s. In other words, $H \rightarrow hh$ branching is negligible for high value of $\tan \beta$.

Here, we are interested to study the effect of heavy MSSM Higgs H production which decays into a pair of h . In MSSM this decay mode is particularly important in the mass window $250 \text{ GeV} < M_H < 400 \text{ GeV}$ for low value of $\tan \beta$. Above $M_H > 350 \text{ GeV}$, its decay to top quark opens up and eventually becomes the dominant one. To illustrate this point, we present the plot for branching ratio of H for two values of $\tan \beta = 3$, and 5 in Fig. 1 assuming $\sin(\beta - \alpha) = 1$. For spectrum generation and decay/branching calculations, we use SUSY-HIT [21]. It is clear from Fig. 1 that for $\tan \beta = 3$ (5) $\text{BR}(H \rightarrow hh)$ can be as high as 64 (25)%. For $\tan \beta = 2$, branching to lighter Higgs can go up to 83% while at moderate $\tan \beta$ ($= 10$) its maximum value reduces to only 2%. For small $\tan \beta$, H branching to $t\bar{t}$ is important when it is kinematically allowed, but for large

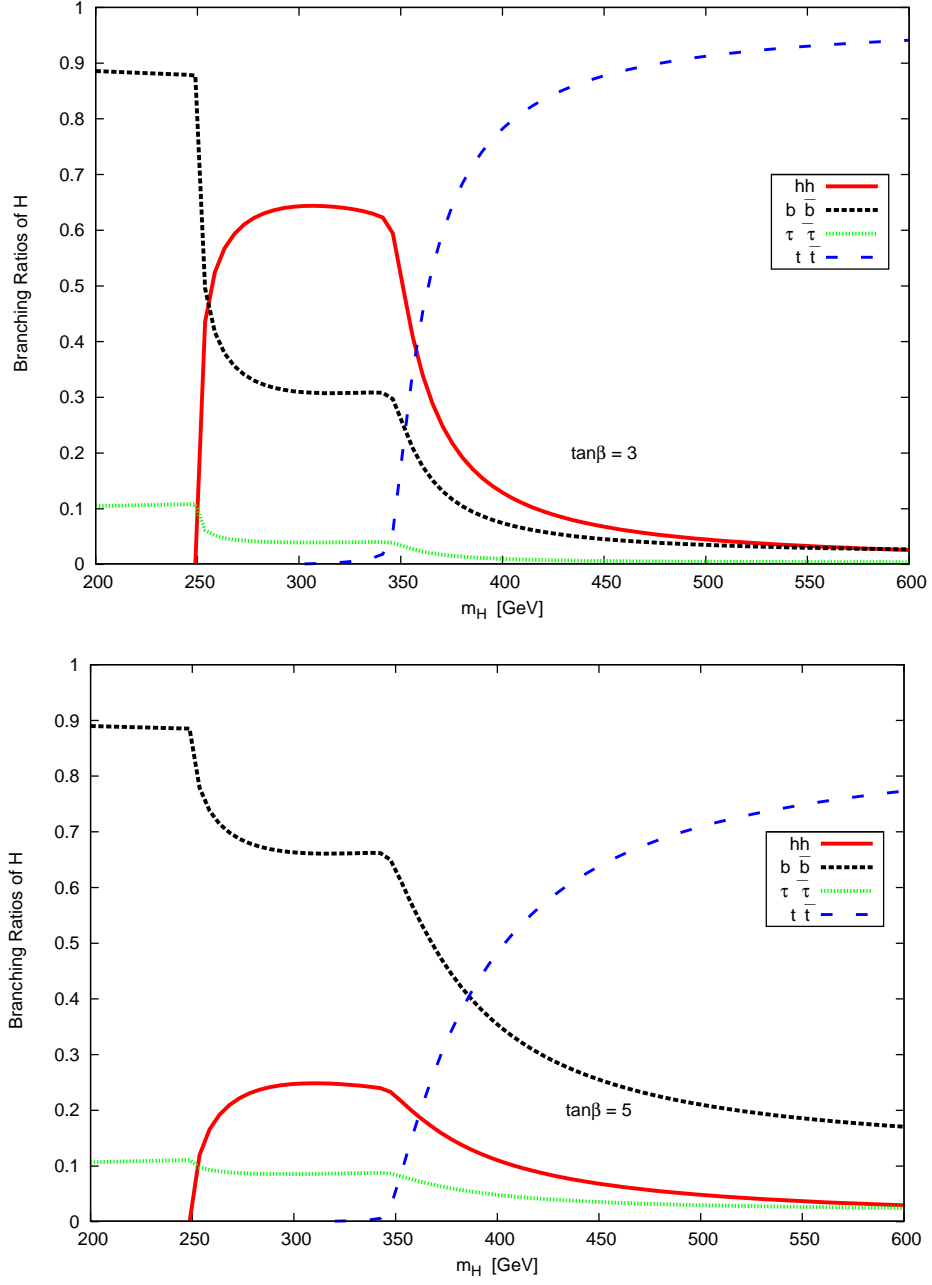


Figure 1: *Branching Ratios for heavy CP even Higgs (H) for $\tan\beta = 3$ and 5. Results are given in the limit $\beta - \alpha = \pi/2$.*

$\tan\beta$, $\text{BR}(H \rightarrow b\bar{b})$ always dominates (for example, $\text{BR}(H \rightarrow b\bar{b})$ varies between 70 to 90 % for $\tan\beta=10$). In Table 1 we present the variation of branching ratio $\text{Br}(H \rightarrow hh)$ for different values

of M_H and $\tan \beta$ (see last three columns).

M_H (GeV)	σ_{NNLO} (pb)			$Br(H \rightarrow hh)$		
	$\tan \beta = 2$	$\tan \beta = 3$	$\tan \beta = 5$	$\tan \beta = 2$	$\tan \beta = 3$	$\tan \beta = 5$
250	3.970	2.416	2.459	0.55	0.43	0.12
275	3.347	1.945	1.798	0.82	0.62	0.22
300	2.936	1.635	1.371	0.83	0.64	0.25
350	2.854	1.460	0.959	0.51	0.50	0.22
400	2.558	1.233	0.676	0.08	0.13	0.11
450	1.792	0.844	0.431	0.04	0.07	0.07
500	1.191	0.554	0.273	0.03	0.05	0.05

Table 1: σ_{NNLO} is the NNLO cross-section of single H production from gluon fusion and bottom quark annihilation. Branching ratios of heavy CP even Higgs to di-Higgs final state ($Br(H \rightarrow hh)$) is calculated for different values of $\tan \beta$ assuming $\beta - \alpha = \pi/2$ with $M_h = 125$ GeV.

Production cross-section of H depends on $\tan \beta$ through heavy quark couplings. The dominant contribution to single H production mainly comes from gluon-gluon fusion although, for large or moderate $\tan \beta$, the bottom quark annihilation to H ($b\bar{b} \rightarrow H$) cross section can be substantial [22]. We compute the NNLO cross-section of single H production coming from gluon fusion and bottom-quark annihilation using SusHi (version 1.3.0) [23] with MSTW 2008 (NNLO) PDF [24–26]. The single production cross section of H can be much larger than SM hh production, for example, $\sigma(gg + b\bar{b} \rightarrow H)$ is 1635 fb for $M_H = 300$ GeV with $\tan \beta = 3$. For the same H mass, this cross section reduces to 1371 fb for $\tan \beta = 5$. The total cross section $\sigma(gg + b\bar{b} \rightarrow H)$ for different benchmark points are presented in Table 1.

3 Benchmark points in pMSSM model

We are interested to point out that the low $\tan\beta$ region in the MSSM is not well favoured due to the fact that in this region of the parameter space, it is very difficult to achieve the lighter Higgs mass to ~ 125 GeV assuming low supersymmetry (SUSY) breaking scale (M_S). For example, with $M_S = 1$ TeV and for $\tan\beta = 3$, the lightest Higgs boson mass is just about ~ 99 GeV (assuming trilinear coupling $A_t = 0$ GeV). However, it is possible to get 125 GeV Higgs mass by lifting the SUSY scale to 5 - 100 TeV even with small $\tan\beta$ [27, 28]. This type of high scale SUSY scenario has become particularly attractive in the context of recent discovery of 125 GeV Higgs boson which requires somewhat higher value of SUSY scale (typically $M_S > 1$ TeV) in contrast to the pre-LHC era, the absence of flavour changing neutral current and non observation of supersymmetric particles at the LHC. For these reasons, we define our benchmark points with large values of common scalar mass (a few TeV) for further analysis. We do not consider any particular form of SUSY breaking and we choose benchmark points in the phenomenological MSSM model (pMSSM). Below we talk about our choices of input parameters.

We set the values of gaugino mass parameters as $M_1 = 1$ TeV, $M_2 = M_3 = 3$ TeV. All squark and slepton masses (both L and R types) including third generations are assumed to be heavy and degenerate ($M_{\tilde{q}} = M_{\tilde{q}_L} = M_{\tilde{q}_R} = M_{\tilde{l}_L} = M_{\tilde{l}_R}$). To achieve the Higgs mass we vary the common scalar mass $m_{\tilde{q}}$ (equivalent to M_S or SUSY scale) from 3 TeV to 6 TeV. The other fixed parameters are $\mu = 1.5$ TeV and the trilinear coupling $A_t = 0$ (also the remaining trilinear couplings $A_\tau, A_b, A_u, A_d, A_e$ parameters are all set to zero.) In our analysis the relevant SM parameters considered are $m_t^{pole} = 173.2$ GeV, $m_b^{\overline{MS}} = 4.19$ GeV and $m_\tau = 1.77$ GeV.

In Table 2, we present the relevant input parameters and output Higgs masses, Higgs mixing angle, $\sin(\beta - \alpha)$ etc. for benchmark points BP1-BP5 with $M_H = 275, 350, 450, 500$ and 600 GeV respectively. From Table 2, it is clear that $\sin(\beta - \alpha)$ is very close to unity. The NNLO cross-section of single H production (σ_{NNLO}), coming from gluon fusion and bottom-quark annihilation, has been presented in the last column of Table 2. We have computed σ_{NNLO} using SusHi (version 1.3.0) [23].

In the presence of mixing with the heavy CP even Higgs boson, the properties of the 125 GeV Higgs can change. It is thus important to check the branchings and production cross sections of

Point	Input Parameters			Output					σ_{NNLO} (pb)
	$M_{\tilde{q}}$ (GeV)	M_A (GeV)	$\tan\beta$	M_h (GeV)	M_H (GeV)	α	$\sin(\beta - \alpha)$	$Br(H \rightarrow hh)$	
BP1	4350	272	5	125.1	275	-0.2734	0.9971	28.2	2.265
BP2	5820	338	2	125.1	350	-0.5589	0.9955	45.6	3.939
BP3	4125	449	6	125.0	450	-0.1923	0.9996	6.1	0.472
BP4	4275	498	5	125.0	500	-0.2254	0.9996	5.1	0.328
BP5	4275	599	5	125.0	600	-0.2169	0.9998	2.2	0.131

Table 2: Input parameters and output masses, mixing angles, values of $\sin(\beta - \alpha)$ for benchmark points BP1-BP5. $Br(H \rightarrow hh)$ represents the branching ratios for heavy Higgs to light Higgs pair. σ_{NNLO} is the NNLO cross-section of single H production from gluon fusion and bottom quark annihilation.

125 GeV Higgs in our case. Before presenting the analysis for heavy Higgs in the next section, now we summarise the properties of the 125 GeV Higgs and MSSM effects on hhh couplings for our selected benchmark points.

Among the four main production modes of the Higgs boson at the LHC : gluon-gluon fusion (ggF), vector boson fusion (VBF), associated production with W/Z bosons (VH) and top quarks ($t\bar{t}h$); ggF has the largest cross section and VBF process is the next dominant one. ATLAS and CMS collaborations have analysed the LHC data in five decay channels ($X\bar{X}$): $X\bar{X} = \gamma\gamma, WW^*, ZZ^*, b\bar{b}, \tau^+\tau^-$. They have also presented the signal strength ($\mu_{ggF/VBF/VH/t\bar{t}h}$) in individual/combine mode by measuring the $ggF/VBF/VH/t\bar{t}h$ rate with normalized by the SM predictions. In this work, we mainly focus on ggF and VBF production modes for illustration purpose.¹

Signal strength in a particular channel $X\bar{X}$ is defined as

$$\mu_{ggF/VBF}(X\bar{X}) = \frac{\Gamma(h \rightarrow gg/WW)}{\Gamma(h_{SM} \rightarrow gg/WW)} \times \frac{BR(h \rightarrow X\bar{X})}{BR(h_{SM} \rightarrow X\bar{X})} \quad (1)$$

¹Both ATLAS and CMS group have measured signal strength in $b\bar{b}$ channel only from associated production with W/Z bosons (VH) process.

$h \rightarrow X\bar{X}$	ATLAS		CMS	
	μ_{ggF}	μ_{VBF}	μ_{ggF}	μ_{VBF}
$\gamma\gamma$	1.32 ± 0.38 [30]	0.8 ± 0.7 [30]	$1.12^{+0.37}_{-0.32}$ [31]	$1.58^{+0.77}_{-0.68}$ [31]
ZZ^*	$1.66^{+0.51}_{-0.44}$ [32]	$0.26^{+1.64}_{-0.94}$ [32]	$0.80^{+0.46}_{-0.36}$ [33]	$1.70^{+2.2}_{-2.1}$ [33]
WW^*	$1.02^{+0.29}_{-0.26}$ [34]	$1.27^{+0.53}_{-0.45}$ [34]	$0.74^{+0.22}_{-0.20}$ [35]	$0.60^{+0.57}_{-0.46}$ [35]
$b\bar{b}$	$0.51^{+0.40}_{-0.37} (\mu_{VH})$ [36]		$1.0 \pm 0.5 (\mu_{VH})$ [37]	
$\tau^+\tau^-$	$1.93^{+1.45}_{-1.15}$ [38]	$1.24^{+0.58}_{-0.54}$ [38]	1.07 ± 0.46 [39]	0.94 ± 0.41 [39]

Table 3: Latest results on signal strength (μ) from LHC 7+8 TeV data for the decay modes $h \rightarrow \gamma\gamma, WW^*, ZZ^*, b\bar{b}$ and $\tau^+\tau^-$. It may be noted that in the ZZ^* channel, signal strength has been presented in two channels: combined $ggF + b\bar{b}h + t\bar{t}h$ final states and combined $VBF + VH$ final states.

where $\Gamma(h \rightarrow gg/WW)$ is the partial decay width used for ggF/VBF mechanism.

We present the experimentally measured values of signal strength (μ) from LHC 7+8 TeV data with integrated luminosity 25 fb^{-1} in Table 3. From the signal strength measurements one can constrain the couplings of Higgs with fermions or bosons. The measured μ values indicate that the 125 GeV Higgs is very close to SM like, but still there are several channels where the measured μ values are deviated from SM expectations and the errors are also large. We present the calculated μ values in ggF and VBF mode for our selected SUSY benchmark points in Table 4. We can see from Table 4 that in case of BP1, the signal strengths deviate appreciably from SM expectations although these values are within 2σ range of experimental results (see Table 3). As we increase M_A or M_H , the $\mu_{ggF/VBF}$ values become close to unity. All the benchmark points representing M_H in the range 275 - 600 GeV, satisfy the latest data for 125 GeV Higgs within 2σ limits.

MSSM effects on hhh couplings: Apart from the Higgs boson couplings to the gauge bosons and fermions, the trilinear and quartic couplings are also affected by the presence of MSSM. The trilinear couplings (λ_{hhh}) in SM and MSSM (with normalized to $\lambda_0 = [\sqrt{2}G_F]^{1/2}M_Z^2$) are given by [8, 40]:

$$SM \quad : \quad \lambda_{hhh}^{SM} = \frac{3M_h^2}{M_Z^2} \quad (2)$$

$h \rightarrow X \bar{X}$	BP1		BP2		BP3		BP4		BP5	
	μ_{ggF}	μ_{VBF}	μ_{ggF}	μ_{VBF}	μ_{ggF}	μ_{VBF}	μ_{ggF}	μ_{VBF}	μ_{ggF}	μ_{VBF}
$\gamma\gamma$	0.68	0.71	0.84	0.90	0.90	0.90	0.93	0.93	0.99	0.98
ZZ^*	0.67	0.70	0.82	0.88	0.89	0.89	0.92	0.91	0.98	0.97
WW^*	0.66	0.69	0.81	0.87	0.88	0.88	0.91	0.91	0.97	0.96
$b\bar{b}$	1.09 (μ_{VH})		1.01 (μ_{VH})		1.01 (μ_{VH})		0.99 (μ_{VH})		0.97 (μ_{VH})	
$\tau^+\tau^-$	1.14	1.20	1.04	1.12	1.09	1.09	1.09	1.08	1.07	1.06

Table 4: Signal strengths for the decay modes $h \rightarrow \gamma\gamma, WW^*, ZZ^*, b\bar{b}$ and $\tau^+\tau^-$ for benchmark points BP1-BP5.

$$MSSM : \quad \lambda_{hhh} = 3 \cos(2\alpha) \sin(\beta + \alpha) + \frac{3\epsilon \cos^3 \alpha}{M_Z^2 \sin \beta} \quad (3)$$

where the mixing angle α and β are related by:

$$\tan 2\alpha = \frac{M_A^2 + M_Z^2}{M_A^2 - M_Z^2 + \epsilon / \cos 2\beta} \tan 2\beta \quad (4)$$

and the radiative corrections in the leading m_t^4 one-loop approximation, parametrized by [8]

$$\epsilon = \frac{3G_F}{\sqrt{2}\pi^2} \frac{m_t^4}{\sin^2 \beta} \log \left[1 + \frac{M_S^2}{m_t^2} \right] \quad (5)$$

The Higgs pair production cross sections ($gg \rightarrow hh$) has dependence on the λ_{hhh} which is determined by $M_A, \tan \beta$ and M_S . Di-Higgs production cross section can be enhanced/reduced from SM value, depending on the MSSM parameters. For example, with $\lambda_{hhh}/\lambda_{hhh}^{SM} = 0, 1$ and 2 , the Higgs pair production cross sections are 71 fb , 34 fb and 16 fb respectively [5]. Cross section at the lower values of λ_{hhh} increased due to the destructive interference of box and triangle diagrams involving $gg \rightarrow hh$.

We show the variation of $\lambda_{hhh}/\lambda_{hhh}^{SM}$ as a function of M_A for two sets of fixed $\tan \beta$ and SUSY scale (M_S) in Fig. 2. The values of $\tan \beta$ and M_S are motivated from our selected benchmark points (see Table 2). For $\tan \beta = 2$, the ratio is very close to unity for $M_A > 350 \text{ GeV}$ and for $\tan \beta = 5$, the ratio varies from 1.2 to 1.35 depending on M_A .

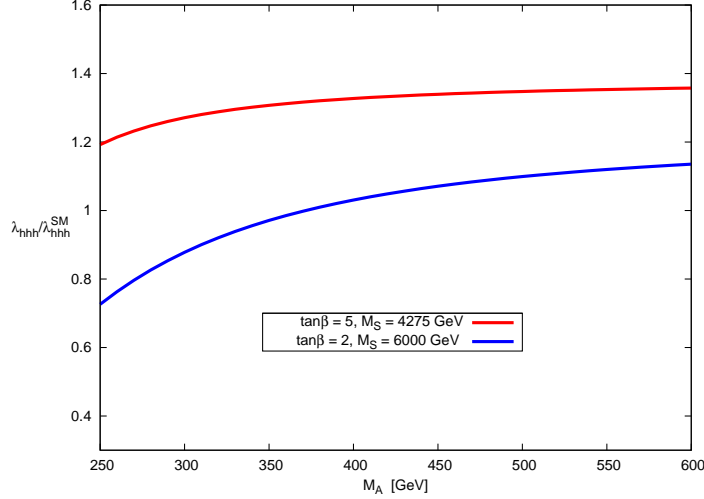


Figure 2: Variation of $\lambda_{hhh}/\lambda_{hhh}^{SM}$ with M_A . Red (blue) line represents scenarios with $\tan\beta = 5$ (2) and $M_S = 4275$ GeV (6000 GeV).

4 Analysis and Results

At the leading order, SM Higgs pair production occurs either through gluon fusion to hh (via top quark box diagram) or gluon gluon to virtual Higgs (mediated by top quark triangle diagram) and its splitting into a pair of Higgs bosons. The contribution of the box diagram is independent of the Higgs self coupling and this also interfere destructively with the later one. At present, the SM Higgs pair cross section is known at the NLO level and it is about 34 fb at the 14 TeV LHC for $M_h = 125$ GeV [29]. As discussed in the previous section, hh production cross-section can be changed depending on MSSM parameters. However, for illustration purpose we only use the SM value.

Let us now discuss potentially detectable final states from Higgs pair production at the LHC. In spite of the large cross section of $b\bar{b}b\bar{b}$ final state, it is very difficult to observe the di-Higgs signal in this channel due to the huge QCD background. On the other hand, fully leptonic final states from h to gauge boson decay, i.e., $h \rightarrow ZZ/WW \rightarrow \text{leptons}$, is not very promising due to small branching fractions of W/Z bosons to leptons. Recent studies using jet substructure tech-

nique show that $b\bar{b}\tau^+\tau^-$ [11] and $b\bar{b}W^+W^-$ [41] channels may be encouraging at the HL-LHC. So far, the most promising channel to observe di-Higgs production is $b\bar{b}\gamma\gamma$ final state, although the branching to this particular channel is very small (about 0.27 %). Observation of this channel is possible due to the high identification efficiency as well as excellent energy measurement of photons so that Higgs candidate in the di-photon invariant mass distribution can be easily separated from the background. The ATLAS collaboration has performed a detailed analysis [5] in this channel closely following the Ref. [10] and according to their estimation di-Higgs (hh) production signal can be observed at $\sim 3\sigma$ level at the HL-LHC ² In this work, we only focus on the most promising final state, i.e., $b\bar{b}\gamma\gamma$ channel.

By comparing cross sections of single H production (see Table 1) and direct pair production of h , we can see that single H cross section can be up to two orders in magnitude higher than the hh cross section. Depending on the branching $H \rightarrow hh$, H production can, in principle, contaminate the signal of direct hh production and therefore affect the measurement of self coupling of 125 GeV Higgs (h). For illustration purpose, we take the benchmark points BP1 - BP5, introduced in Sec. 3 (see Table 2) and compare with SM hh production in the $b\bar{b}\gamma\gamma$ channel ³.

SM parton level hh events with $M_h = 125$ GeV have been generated using MadGraph5 [44] at the 14 TeV LHC using the model file of “Higgs Pair Production” [45] which includes both top quark box and triangle diagrams. For generating MSSM signal (i.e., single H production) we have used the MC generator PYTHIA [46]. All SM and SUSY events are showered and hadronized by PYTHIA and cross sections are scaled to NLO/NNLO values given in Table 2 for different benchmark points. For object reconstruction, we use fast detector simulator package Delphes3 [47] ⁴. Details of the analysis cuts and efficiencies, following the ATLAS analysis [5], are discussed below.

Events containing two b -jets and two photons are selected. Selection requirements of b -jets are $p_T > 40$ (25) GeV for leading (sub-leading jets) and $|\eta| < 2.5$. It is assumed that b -tagging

²The dominant SM background in this process is $t\bar{t}h$. It may be noted that we have only generated SUSY $H \rightarrow hh$ signal and SM hh production processes and SM backgrounds are not analysed in our work.

³All these benchmark points are well below the current LHC bound on heavy Higgs [42, 43].

⁴Jets are reconstructed with anti- k_t algorithm with $R = 0.4$.

efficiency is 80%. Photons are selected with $p_T > 25$ GeV, $|\eta| < 2.5$ and they satisfy the isolation requirement. Following ATLAS analysis [48] photon candidate is removed if more than 4 GeV of transverse energy is observed within a cone with $\Delta R = 0.4$ surrounding the photon. The photon identification efficiency is assumed to be 80%. Separation cuts between $bb, b\gamma, \gamma\gamma$ pair ($\Delta R(b, b), \Delta R(b, \gamma), \Delta R(\gamma\gamma)$) are greater than 0.4. Criteria for reconstructing the Higgs mass are: $50 \text{ GeV} < M_{b\bar{b}} < 130 \text{ GeV}$, $120 \text{ GeV} < M_{\gamma\gamma} < 130 \text{ GeV}$, where $M_{b\bar{b}}$ and $M_{\gamma\gamma}$ are the invariant masses of $b\bar{b}$ and di-photon respectively. Finally, a lepton veto is also applied. After imposing the above cuts we obtain approximately 13.5 SM hh events at the 14 TeV LHC with integrated luminosity $\mathcal{L} = 3000 \text{ fb}^{-1}$ which is fairly consistent with the ATLAS result [5]. On the other hand, the same cuts select 260, 779, 13, 7 and 2 events for $BP1, BP2, BP3, BP4, BP5$ respectively with the same luminosity. We find that the MSSM single H production can change the di-Higgs production cross section and this effect is significant in the H mass range 250-600 GeV in the low $\tan \beta$ region.

Counting of the number of $b\bar{b}\gamma\gamma$ events in all these benchmark points shows moderate to huge excess over SM cross section, although it is not possible to identify the origin of the excess from this counting itself. It is therefore important to separate out the direct hh cross section from the MSSM heavy Higgs contribution. As the decay width of H is small (at most a few GeV), one may try to separate out the direct hh events from the MSSM H events by identifying it in the $b\bar{b}\gamma\gamma$ invariant mass (M_{hh}) distribution [16,17].

In Fig.3 we present the invariant mass distribution of reconstructed hh pair of SM events and SUSY events for four benchmark points (BP1-4)⁵. We can identify the clear peaks of heavy Higgs for $BP1$ and $BP2$. We can see that the hh invariant mass distribution spreads over 100-150 GeV range, although, the H decay width is small (about a few GeV). This broadening mainly comes from the reconstructed h from the b quark pair and this can not be reduced further because of the limitation of the hadronic calorimeter. It is therefore not possible to sharpen the H mass peak in this channel. However, one can remove most of the H events by putting a cut on the hh invariant mass distribution around H peak, although, the same cut may remove some amount of direct hh

⁵The number of events for BP5 is very small and it is not shown in Fig.3.

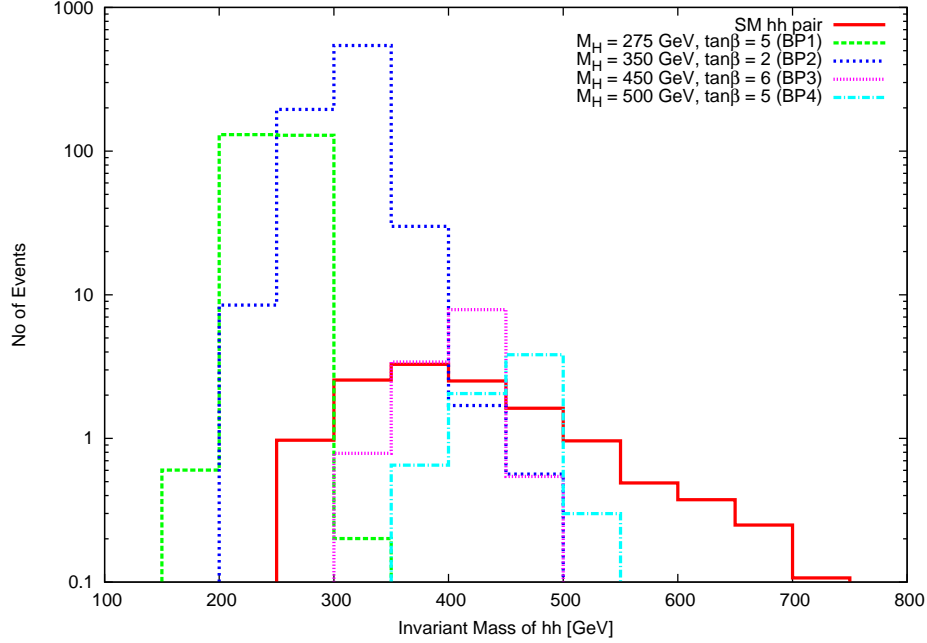


Figure 3: *Invariant mass distribution of SM hh events and the events coming from single H production for different SUSY benchmark points. Events are obtained after the basic cuts/Higgs reconstruction (see text) with $\mathcal{L} = 3000 \text{ fb}^{-1}$ at 14 TeV HL-LHC.*

events. Depending on the values of M_H and $\tan\beta$ we may think of four possibilities:

Scenario A: MSSM contribution is very large compared to SM (for example, consider *BP1*). The excess events over direct hh events can be separated by imposing a cut on di-Higgs invariant mass and in that case direct hh pair events may be marginally affected by this cut. In case of *BP1*, one can remove almost all of the SUSY contribution (259 out of 260) by rejecting the events in the M_{hh} bin of 200-300 GeV. However, this cut only reduces the SM events by one. Here we can separately measure both contributions and the determination of parameters in the Higgs sector may be possible in this case.

Scenario B: In this case SUSY contribution is also large (for example, see *BP2*) although invariant mass cut may not help us to separate out these two contributions. The position of the H peak is such that the events coming from the direct hh production also large around M_H . In case

of *BP2*, there are 770 events (total events = 779) in the region $250 \text{ GeV} < M_{hh} < 400 \text{ GeV}$ and if we reject events of these bins, the SM hh events reduces to 7 from 13.5. One possibility to separate these two contributions is to fit the H peak and continuum hh events simultaneously. However, the number of direct hh events may not be statistically sufficient for this procedure. However, we can clearly identify existence of H from this measurement.

Scenario C: SUSY contribution is comparable or slightly smaller than SM in this case (for example, see *BP3*, *BP4*). Identification of distinct reconstructed peak of H is difficult because of the poor statistics. The slight excess which comes from H , can be manifested as an enhancement of h self coupling. However, many different new physics models can give rise to enhancement of h self-coupling and it is thus difficult to identify the presence of heavy Higgs in this scenario. Invariant mass cut also do not help to identify the MSSM contribution in this case. while it also removes 8 direct hh events. Again a cut $350 \text{ GeV} < M_{hh} < 500 \text{ GeV}$ can remove 7 events of *BP4* while it also removes about 7 direct hh events. This should be regarded as the most challenging scenario in the context of the measurement of h self coupling.

Scenario D: If we increase M_A above 500-550 GeV, the number of events from direct hh production reduces considerably and about 2-3 events survive. If $\tan \beta$ is in the range ~ 5 or more (see *BP5*), H production cross section is also small and it is very difficult to observe the H resonance in that region. In case of *BP5*, we can expect 1-2 events which is not statistically significant. For very small value of $\tan \beta$ (< 3), there is a chance to observe the heavy Higgs boson resonance due to the enhancement of production cross section.

5 Discussions

In this paper we have studied how the decay of heavy MSSM Higgs can contribute the measurement of self coupling of lighter Higgs boson. The branching ratio $H \rightarrow hh$ can be sizable in the low $\tan \beta$ region and it can affect the direct hh signal if the mass of H lies in between 250-600 GeV. Depending on the parameter space, MSSM signal can be very large compared to direct hh production and in that case, clear identification of heavy Higgs boson is possible. However, we have identified a region

in the parameter space corresponding to $M_H = 400 - 600$ GeV with low $\tan\beta$ where the MSSM contribution is small but non-negligible. In such scenarios, the identification of H is difficult and an excess in cross sections may be explained in terms of enhancement of h self coupling. This should be regarded as the most challenging scenario and further studies are required in this direction. Before concluding we are interested to point out a few relevant issues:

- In our work we rely on the default smearing parameters implemented in Delphes3. However, in case of HL-LHC, there can be some changes in the LHC detector design and one may expect more smearing effect compared to the conventional case. To check the effect of smearing we increase the default ATLAS smearing parameters of ECAL and HCAL by a factor of 25% and study its effect. We find that our result is almost unaffected under this change.
- One may think of discovering heavy Higgs bosons in different channel, for example $t\bar{t}$ final state which is the dominant decay mode for $M_H > 350$ GeV. However, in that case, the main background is SM top quark production. Assuming that the reconstructed heavy Higgs mass may lie within 100 GeV mass range, our naive estimation shows that the ratio of SM $t\bar{t}$ background and signal can be as large as 100-1000 at the parton level, which makes it hard to detect in this mass range and it requires a dedicated study. It is also important to identify the other Higgs bosons A and H^\pm in this mass range and jet substructure technique can be useful in this purpose [49].
- In this paper we consider heavy CP even Higgs production and its decay to 125 GeV Higgs in the $b\bar{b}\gamma\gamma$ channel. However, the same signal may come from other production processes like $pp \rightarrow A \rightarrow Zh, Z \rightarrow b\bar{b}, h \rightarrow \gamma\gamma$. In the Higgs self coupling measurement we accept $b\bar{b}$ invariant mass window in the range 50 GeV to 130 GeV and $Z \rightarrow b\bar{b}$ can easily contribute to the measurement. However, Zh production can be seen in leptonic channels, for example, $\mu\mu\gamma\gamma$ etc. and this information can be used to separate out such contribution from real hh production.
- Heavy Higgs production and its decay to hh can interfere with direct hh production process. This may be seen as dip/rise in the di-Higgs invariant mass distribution around M_H mass at the parton level. However, we have checked that this effect is smeared out by hadronization and detector effects and it is difficult to identify the interference effect.

- In this paper we only consider heavy Higgs to hh decay. Depending on the parameter space, several potentially observable decay modes [50, 51] may open and in principle, MSSM Higgs bosons can be discovered in other channels. A detailed study is beyond the scope of this paper and these issues will be considered in a separate work [49].

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